12-2020

Improving engineering education through cyber-physical systems: instrumentation and control of a unit operations laboratory

Shelby Musselman
University of Tennessee at Chattanooga, ffb176@mocs.utc.edu

Improving engineering education through cyber-physical systems: instrumentation and control of a unit operations laboratory

Shelby Janet Musselman

Departmental Honors Thesis
The University of Tennessee at Chattanooga
Department of Civil and Chemical Engineering

Examination Date: 11/11/2020

Bradley J. Harris
Assistant Professor of Civil and Chemical Engineering
Thesis Director

Michael Danquah
Professor and Director of Chemical Engineering
Department Examiner

Table of Contents

ABSTRACT

A cyber-physical system (CPS) is a network of physical devices that are monitored or controlled by computer-based algorithms. A key enabler for future technology developments, CPS is an interdisciplinary research area that engages a broad spectrum of disciplines and could bring about revolutionary changes in domains such as energy, environment, and healthcare [1, 2] Using CPS to develop smart, connected products through hierarchies such as internet of things (IoT) allows for integration of systems and provides open access to data subsets for digital service applications. This technology has the potential to transform our everyday lives (e.g., smartphones, activity trackers), our communities (e.g., self-driving cars, smart cities), and even our future (e.g., clean energy, space exploration). The Dr. Jim Henry Chemical Engineering and Control Systems Laboratory located at the University of Tennessee at Chattanooga (UTC) is being modernized by integrating National Instruments (NI) myRIO-1900s with NI LabVIEW. Stations currently using these technologies are: Multi Tank Level System (MTLS), Continuously Stirred Tank Reactor (CSTR) Train, Absorption Column, and Pump Flow. A new Adsorber station is also currently under development. Using CPS, students have access to pilot-scale engineering systems that they can monitor and control in the laboratory.

UTC's chemical engineering program is continuously renovating the Dr. Jim Henry Chemical Engineering and Control Systems Laboratory. These renovations will increase student productivity and efficiency while providing a superior learning experience for the students conducting experiments in the lab. Efficiency and ease-of-use is very important for maximizing the academic performance of a diverse student population at UTC. The CECS serves students from a diverse range of socioeconomic backgrounds who are at different stages in life. Of particular relevance is the enactment of the Tennessee Promise, a scholarship and mentorship program that provides last-dollar scholarships for low-income students to attend any state

community college [3]. This means that the number of students who will transfer to four-year universities like UTC will grow exponentially in the coming years. Transfer students face unique barriers to success, including economic hardships that require part- or full-time employment [4]. The portability and convenience of remote access can not only positively affect student education in laboratory courses, but their overall academic performance as well. In addition, this remote laboratory will serve as a showcase of the UTC CECS's laboratory capabilities for local high schools and local industry professionals. It will also eventually be made available to interested parties across the nation and abroad. Thus, this project closely aligns with the University's mission, as UTC is a metropolitan university that strives to provide a nurturing environment that connects students, community, and opportunity.

This undergraduate departmental honors thesis will present initial work towards transforming the Dr. Jim Henry Laboratory into a remote laboratory accessible to students from UTC and beyond. Specifically, this project presented here includes the renovation of the Absorption Column as well as initial design and testing of the Adsorber.

CHAPTER 1: Scope of Work

Initial Focus

The initial focus of this project was to integrate the Dr. Jim Henry Chemical Engineering and Control Systems Laboratory located at the University of Tennessee at Chattanooga (UTC) with National Instrument's (NI) myRIO-1900 with PTC's Thingworx: Internet of Things (IoT) Platform to implement existing lab stations with remote capabilities. This was to be achieved through the NI IoT Education Beta Program. The Beta Program was to provide undergraduate researchers with the tools and exercises needed to connect the acquired and processed data to properties of Things that display this information onto the IoT Platform. This connection would enable a user to control lab station experiments remotely and monitor and analyze data with the use of their personal devices (such as a laptop, smartphone, or tablet) from anywhere at any time. This remote implementation planned to enhance UTC students' educational experience by providing them with the opportunity to conduct experiments remotely at the convenience of each student's personal schedule using their personal devices. However, the Beta program which had already been implemented into a Multi Tank Level System (MTLS) and Continuously Stirred Tank Reactor (CSTR) was ended by PTC, so these systems no longer have remote capabilities.

Shift in Focus

With remote accessibility no longer being an option in the short term, the focus shifted towards re-designing the existing Absorption Column for operation via NI's cutting-edge myRIO-1900 microcontroller. As these devices are WiFi- and Bluetooth-enabled, the station can easily be put online for remote access once a new solution is identified. In addition, a recently donated oxygen purifier that had been disassembled and reconfigured for use as an Adsorption station was to be outfitted with a myRIO and deployed for laboratory use.

The initial plan was to bring the Adsorber system to a working state and have a series of experimental modules ready for launch in the Unit Operations Laboratory (ENCH 3350) in Fall 2020. However, when the COVID-19 pandemic came to Chattanooga, students were not allowed on campus and the project was halted. While the CECS was operating with limited personnel, oxygen sensors procured for the Adsorber system arrived on campus but were subsequently lost. New sensors have been ordered, but they will not arrive at UTC until after the Fall 2020 semester ends. In consideration of this, the system will be set up for limited access until future students can finish the station design.

CHAPTER 2: Introduction and Literature Review

Undergraduate STEM Education

Transfer students from community colleges often experience "transfer shock" when starting their studies at 4-year colleges or universities. This generally results in a lower GPA for the students. Financial issues are also a concern many transfer students from community colleges have. Students stated that community college made it easier to attend school and maintain a job [5]. Students need an information and support network that will transition with them when the time arrives. Transfer students often have lower intellectual self-confidence, and this can be improved by introducing them to hands-on learning that helps them to understand more complex topics generally not covered in community college courses [6].

Transfer students at UTC often struggle with Threshold Concepts (TC). These are concepts that can be considered as akin to a portal, opening up a new and previously inaccessible way of thinking about something. It represents a transformed way of understanding, interpreting, or viewing something without which the learner cannot progress [7]. These Threshold Concepts are essential in a student's understanding, and without understanding these concepts, students cannot move forward in their studies of the discipline [8]. Having students engage in hands-on modules in Chemical Engineering laboratories will expose students to these threshold concepts and allow for a better understanding of them [9].

The onset of information technology has brought about swift changes in manufacturing and how products are made. Whereas industrial equipment was once made up of only mechanical and electrical parts, it is now a complex system of interconnected hardware, sensors, data storage, microprocessors, and software [10]. Two times in the past 50 years, information technology (IT) has reshaped production and efficiency. The first wave of IT occurred in the 1960s and 1970s; this wave automated activities such as order processing and bill paying [10, 11]. In the 1980s and 1990s, the second wave of IT happened. This was due to the rise of the internet, with its low-cost and pervasive connectivity [11]. We now stand at the edge of the third wave of IT, where "smart, connected products" are changing the industrial landscape [10]. Remotely accessible labs help accommodate diverse students' schedules and learning preferences. Providing a hybrid modality will benefit transfer students in particular who represent a diverse age range, have full-time or part-time jobs, or are parents by including a more accessible method of learning. The portability and convenience of remote access can not only positively affect student education in laboratory courses, but their overall academic performance as well. These renovations will increase student productivity and efficiency while providing a superior learning experience for the students conducting experiments in the lab. Efficiency and ease-of-use is very important for maximizing the academic performance of a diverse student population at UTC.

LabVIEW and NI myRIO-1900

Laboratory Virtual Instrumentation Engineering Workbench, or LabVIEW, uses a visual programming language called G. The code is not written, but rather drawn, and so programmers can experience a wider range of developments [12, 13]. LabVIEW has matured into a general purpose programming language in recent years [12]. There are source communities and forums dedicated to sharing code from LabVIEW and promoting success using the language such as LAVA (LabVIEW Advanced Virtual Architects) [14]. LabVIEW is also compatible with a suite of NI process controls hardware, including the myRIO-1900. The NI myRIO represents an advance in instrumentation, as it places the LabVIEW RIO structure, a universally accepted, industry recognized hardware/software scheme method, squarely in the hands of learners. NI myRIO-1900, used with LabVIEW through its FPGA interface, provides powerful hardware and software that can be used by students to master the concepts of process control.

Absorber Overview

Absorbers bring gas and liquid phases in contact. This is used for converting contaminants in the gas phase into the liquid phase. The entering gas stream contains solutes that are absorbed into the entering liquid stream. The exiting gas stream leaves the column without the solute, while the exiting liquid stream leaves with the solute. Gases flow up through the packed bed, and the scrubbing liquid flows down the bed. The packing provides a large surface area for gas to liquid mass transfer to occur. Packed beds are most commonly used in air pollution control, but they are also used in the chemical, petrochemical, food, pharmaceutical, paper, and aerospace industries [15].

The Dr. Jim Henry Laboratory at UTC, located in EMCS 120, includes a pilot-scale Absorption Column which brings air and water into contact. The water flows down the column from the top while air is pushed up the column from the bottom. Water and air meet in the middle of the column in the scrubbing section, where carbon dioxide absorbs into the water. The exiting streams are air without carbon dioxide and carbon dioxide-rich water. The Absorber system can be seen in figure 1 below.

Figure 1. Absorber System (bottom)

The overall objective of the lab course is to develop a set of parameters for controlling a system using a set of controllable inputs. For the Absorber, the objective is to control air or water flow rates using the air or water valve. In experimental module 1 (SSOC), students collect performance data at steady state over a range of input values. This data is used to inform subsequent studies in modules 2 and 3 (Step and Frequency) where a series of carefully designed experiments are conducted to determine optimal parameters to input into the process controller. Finally, in module 4 (Tuning), students put their results to the test by using the pre-determined controller parameters and observing how well the system operates. The Absorber System Station is used for four different experiments in ENCH 3280L: SSOC, Step, Frequency, and Tuning. Experiment one is done by inputting a run time and a set percent at which the user would like to have the air or water valves open. Experiment two is similar to experiment one, but involves a step change. Experiment three is done by setting an amplitude for the air and water valves which feeds into a sine wave; the user can then see how the flows vary with time. Experiment four is done by setting the flow rate you would like to receive, and inputting parameters to achieve this. Assuming a linear relationship, the user can table the results for average output versus input with a 95% confidence interval, and create a plot compering the experimental output and the model output versus time.

Adsorber Overview

Students may have a basic understanding of absorption and adsorption as underclassmen, but do not necessarily understand the difference between the two before their senior year of classes at UTC. For example, students may have previously been exposed to the concept of absorption during high school or college biology and chemistry labs (for example, the absorption of oil, iron, or drugs are common high school laboratory experiments) [16]. Laboratory modules on adsorption are less common. Some students may be familiar with the silica gel packets that come with electronics to adsorb liquid from the air to protect the equipment, but that is often the extent of their prior knowledge [17]. Because many pollution prevention processes use adsorption, it is useful for all engineering students to have some knowledge of the process. Students who understand the basic principles of adsorption will be better prepared to address the looming environmental challenges of the future.

The Adsorber recently implemented at UTC is a Respironics Millennium Oxygen Concentrator [18]. The figure below shows what the original oxygen concentrator looked like before it was taken apart. This is a type of portable oxygen concentrator which is generally marketed for hospitals and individual use. This oxygen concentrator uses sorbents in two adsorption columns to separate oxygen from nitrogen and other air molecules.

Figure 2. Portable Oxygen Concentrator

The Adsorber system consists of 2 main parts: a compressor and a desiccant bed. The compressor pumps pressurized air into the bed. The desiccant bed is filled with a find adsorbent material similar to sand in shape and size. This material adsorbs the nitrogen and CO_2 in the air and releases it through the bottom of the chamber. All that is left in the chamber is oxygen which flows out through a valve at the top of the bed. The desiccant bed has 2 main chambers. They are operating with a solenoid valve which only allows air to enter one chamber at a time at an interval of 6.25 seconds [19]. After 6.25 seconds, the bed is fully saturated with nitrogen so air enters the other chamber while the first bed releases its nitrogen from the bottom. The valves continue to switch every 6.25 seconds and this allow for continual flow of oxygen out of the chamber. A figure of the Adsorber system after it was taken apart is shown below. The container was opened, all parts were removed and mounted to the wooden boards shown in the picture. The large cylinder is the desiccant bed, and inside the bed there are two chambers as previously discussed. The compressor is on the left, connected to the desiccant bed by red tubing which sends pressurized air into the chamber.

Figure 3. Adsorber system

CHAPTER 3: Results

Absorber

LabVIEW Code

LabVIEW has a front panel and a block diagram. The figure below shows the front panel. This is what the user sees when operating the absorber system. Instructions for operating the system are located in the green and red boxes at the top of the screen. Students must input their UTC ID which is used to send an email to them containing their data. Students can also choose a name for their file for organization in their inbox. Based on what experiment they are running, students have to specify a run time. The experiment will automatically end when the timer runs out. There is a drop down list containing every type of experiment for Control Systems Laboratory. All other widgets except for those on the experiment the student has selected are hidden. The student manually inputs the water and air valve percent open which specifies how much the corresponding valve will open. After specifying the run time and parameters the student would like to use for the experiment, they hit the PUSH TO START button. This begins the experiment until time has elapsed fully. The gauges show the student how much air and water slow is measured at the exit in SLPM (standard liters per minute) and pounds per minute. Once the student has completed their experiment, they have to hit the END ALL button which ends the program and erases their inputs. This way students who use the system next cannot see what parameters the previous students used. If there is an error with the email VI, students will be able to access their file on the computer. This could happen if the input their UTC ID incorrectly, or if Google flags the source of the email and does not send it through.

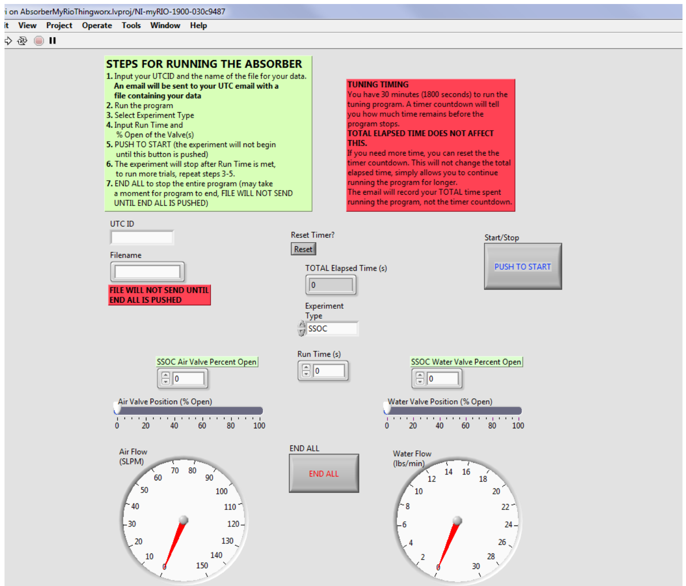

Figure 4. Absorber Front Panel: SSOC

While the system is running, students can see a real time graph of the water flow versus time and air flow versus time. Once the experiment has ended, the students can see the full graph for the experiment they just ran. This is similar to what the students have to make on their own with the data sent in an email. Having the real-time graphs on screen allows for students to see how the water and air flows respond to their inputs. Images for Front Panel code for Tuning, Step, and Frequency experiments can be found in the appendix.

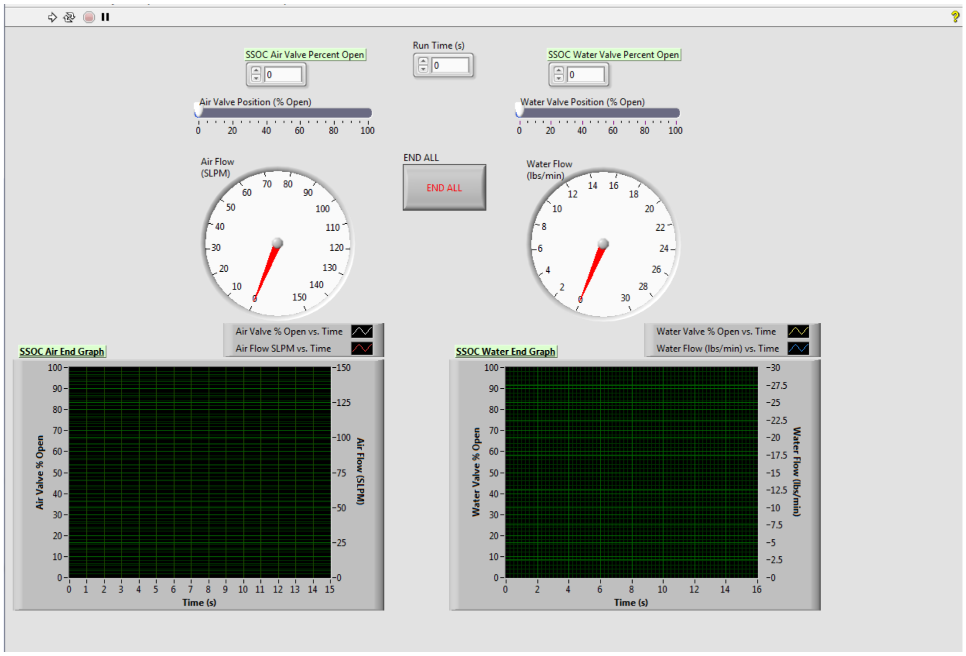

Figure 5. Water and Air Graphs: SSOC

The block diagram is the code that controls everything. This is the actual “code” that controls the system. The block diagram for SSOC is shown below. At the top, the SSOC Air and water valve percent open blocks are connected to what the user inputs on the front panel. From there, basic mathematical operations are performed to transform this percent into a voltage which the myRIO interprets. Channels on the myRIO are opened using LabVIEW’s AI and AO open virtual instruments. The values the student inputted are sent to a Write virtual instrument which sends the calculated voltages to the physical valves and opens them. The air and water flow sensors are hooked up to the myRIO and the values they read are sent back to the system and can be accessed using the Read virtual instrument. More basic calculations are done to turn these voltages into real flow rates, and then are sent to indicators which are depicted on the front panel where students can see their data. The bottom of the screen shows a timer that is used to track the run time. This is wired to the stop button so that when time runs out, the valves close and final data is showed.

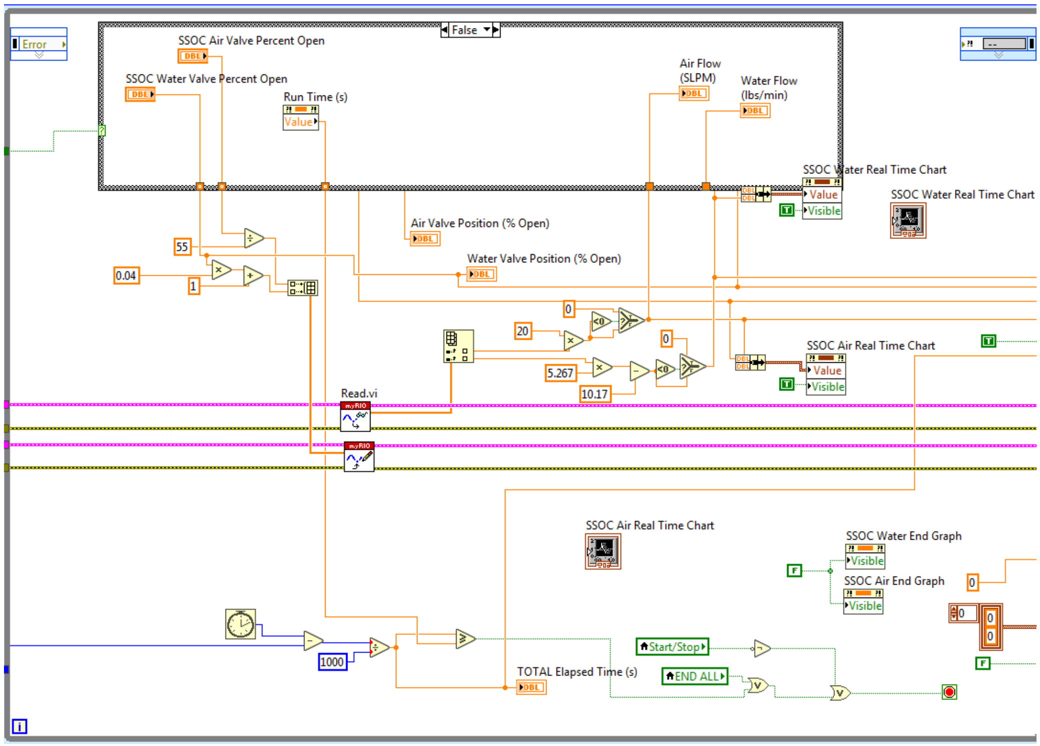

Figure 6. Block Diagram: SSOC

Students receive their data through an email VI. There are several steps to sending this data to the student. The figure below shows

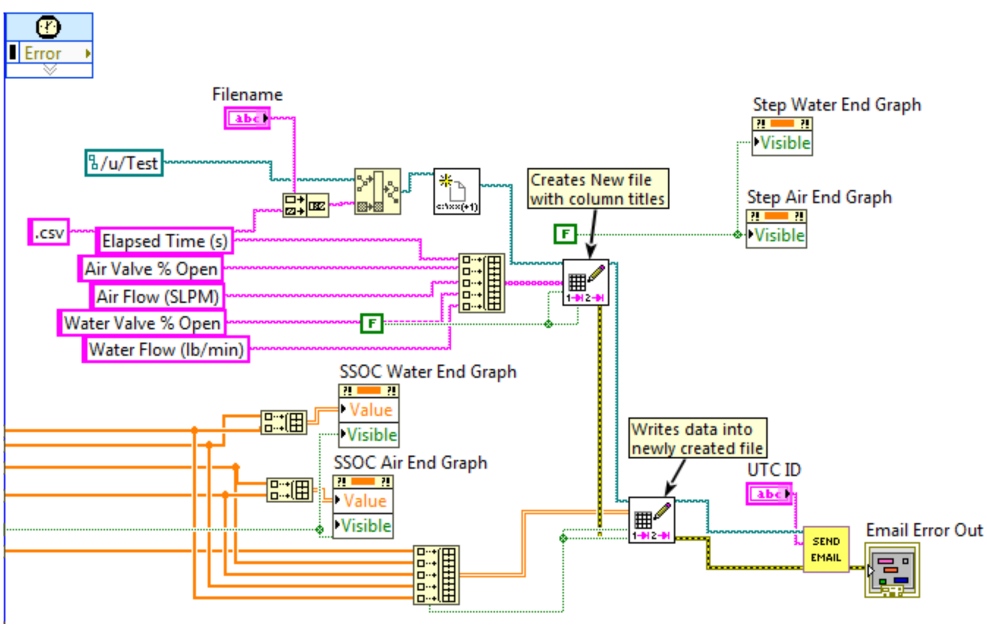

Figure 7. Email VI

There is a USB plugged into the myRIO which is the location files are stored. The location master is /u/Test. The filename students choose will be concentrated into this with .csv to make it a csv file. Then, the path is built which sends it to the /u/Test location on the USB in the myRIO. An array with the titles of all columns in the spreadsheet is made and appended into the new file. The orange strings are the corresponding data from the absorber sent into an array and written into the file. Everything is then sent to a SEND EMAIL VI which uses the student's UTC ID and Google client to send the email to their school email with the file attached.

Hardware and myRIO Implementation

The NI myRIO-1900 provides analog input (AI), analog output (AO), digital input and output (DIO), audio, and power output in a compact embedded device. The myRIO is integrated into the previously existing system which consists of a 16-channel backplane, an 8-channel backplane, an SC-2050 connection board, and screw terminals.

The WDT5 Watchdog is a safety feature installed in the absorber system [20]. Digital signals are sent to the system watchdog timer from the myRIO. The watchdog is reset on negative-going edges of the WDI input. Timeout only occurs when the WDI input does not detect a negative-going transition within the fixed timeout period. The LabVIEW program is coded to continuously send a false signal to the watchdog when the program is running so that it does not timeout. The user cannot operate the air or water valves if timeout occurs.

Figure 8. NI my-RIO 1900 [21]

Previously, the DAQ board in the local computer sent digital and analog signals to the different valves and watchdog timer. The myRIO replaces the need for this by sending AO voltage signals to the water and air valves and receives AI signals from the flow sensors. The program in LabVIEW allows the user to control the percent open of the valves and monitor air and water flow. Connector C on the myRIO is used for the absorber. Signals from the computer are sent to a specific channel on the myRIO and then to the corresponding piece of equipment. Analog output signals are used to control the air and water valves and analog input signals are received from the flow sensors and are sent back to the computer.

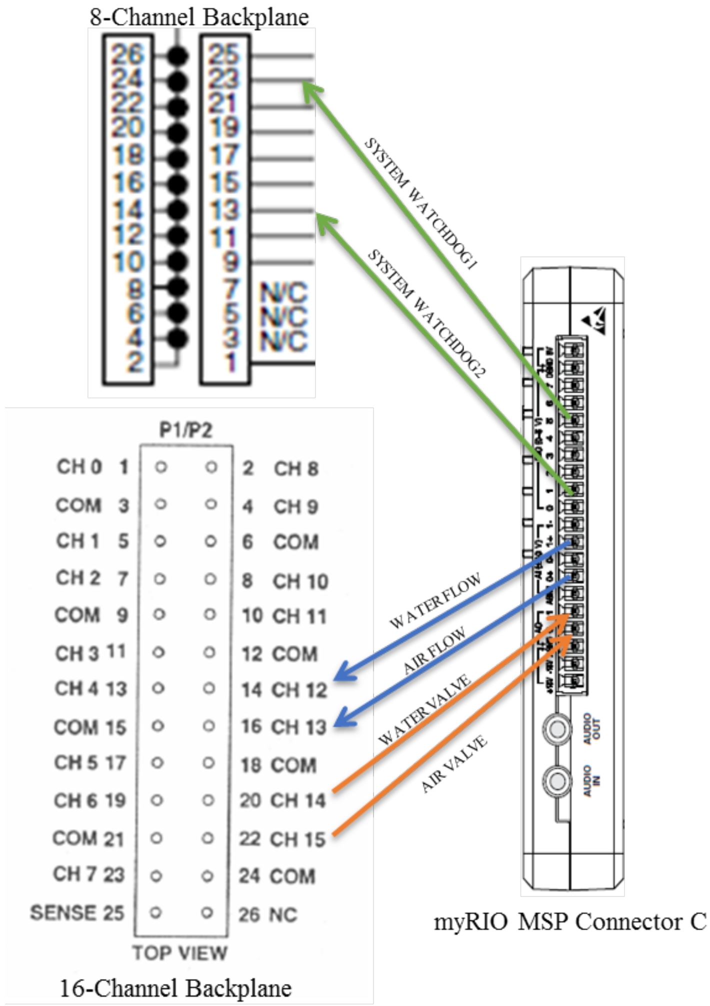

Figure 9. Absorber Wiring Connections [21, 22, 23]

The water valve is shown below. This is connected to channel 14 on the 16-Channel Backplane which leads to the channel C/AO1 on the myRIO. Originally, the valve was wired to be controlled with 4-20 mA, but the myRIO can only output voltages. Moving the jumper JP2 to top 2 pins switched from 4-20mA to 1-5 VDC control signal. This disconnects the 250 Ohm resistor [24]. The valve expects a voltage of 1-5 V. 1 V is completely closed, while 5 V is 100% open. When the user inputs a percentage open to open the water valve, LabVIEW performs the operation V= 0.04(P)+1, where P is the percentage the user input and V is the computed voltage sent to the myRIO.

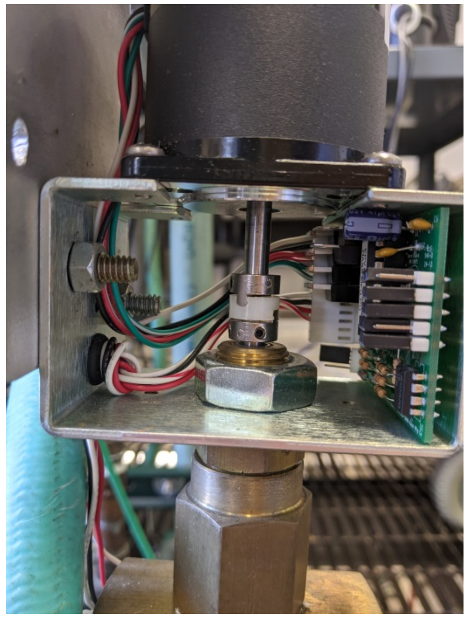

Figure 10. Water Valve

Figure 11 shows the air valve. The air valve is a simple stepping motor mechanically controlled. The control wire is connected to channel 12 on the 16-Channel Backplane which has and isolated current output analog device in that channel [25]. The isolated current device converts the voltage to a current of 4-20mA. This device is there because the stepping motor air valve expects a current, not a voltage and the myRIO only produces voltages. The output channel for this is C/AO0 on the myRIO.

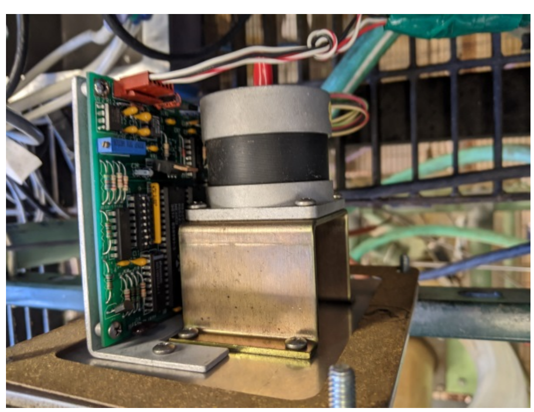

Figure 11. Air Valve

The RFT9739 Field-Mount Transmitter is shown below; this is the water valve. The water valve measures flow in a voltage which is read by the myRIO and converted to a flow rate in lbs/min by F=5.267V- 10.17 in LabVIEW because the voltage the transmitter outputs is -1.9 V minimum and 7.6 V maximum for a flowrate of 0-30 lbs/min which the user can see in the LabVIEW interface.

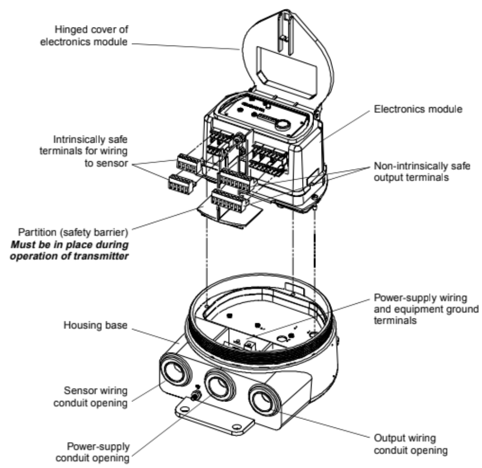

Figure 12. RFT9739 Water Flow Transmitter [26]

Figure 10 shows the air flow sensor from Omega Engineering [27]. The sensor outputs a voltage of 0-5 VDC. This is sent to the myRIO then read in LabVIEW and converted to a flow rate in SLPM by F=20V.

Figure 13. Omega Air Flow Sensor [27]

Experiment Design for Students

IN ENCH 3280L, students perform 4 experiments. The first one is SSOC which is short for Steady State Operating Curve. For this lab, students will have to obtain data for a range of inputs using the absorber then find the response time for the system to each steady state. Experiment one (SSOC) is done by inputting a run time and a set percent at which the user would like to have the air or water valves open. Assuming a linear relationship, the user can table the results for average output versus input with a 95% confidence interval, and create a plot comparing the experimental output and the model output versus time. An example for the air absorber run at 50% is shown below.

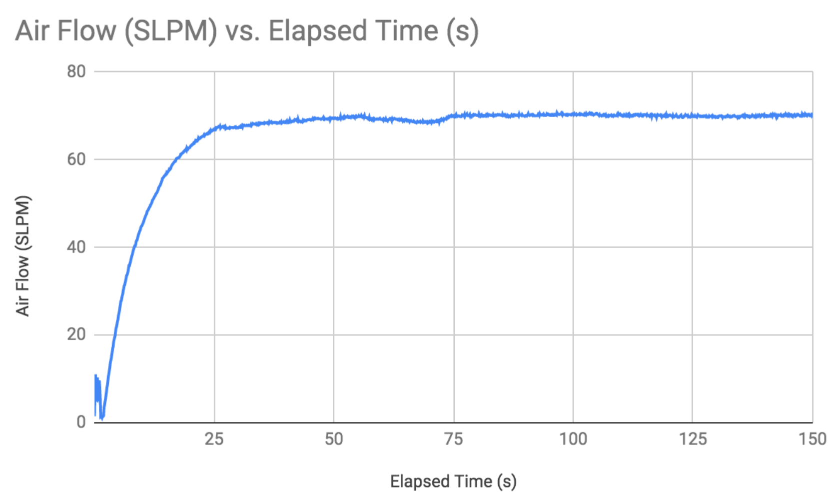

Figure 14. Air Flow vs. Time

The next project is Step, where students have to input a step change into the absorber and determine: the time response of the output function of the system due to a step input, the system's steady state gain, the system's response time, and the system's dead time. They also have to construct graphs to show the step input. From many trials, students can find the response curve from the system shown below.

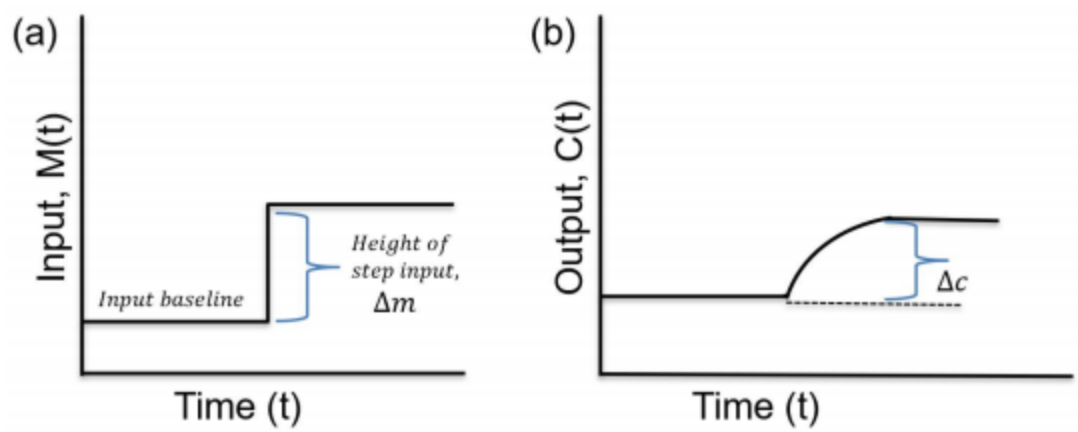

Figure 15. Step Input/Output Response [28]

An example of the parameters shown graphically for a step response is shown in figure 12, where **Δ**c is the difference between the steady state airflow of the output, **Δ**m is the change in the percentage the air is open for the input, 0.632**Δ**c is the number that you add the the lowest steady state output so that you can find the time constant (**τ**), and t0 is the dead time between the step in the input and the change in the output. K was found by dividing **Δ**c by **Δ**m.

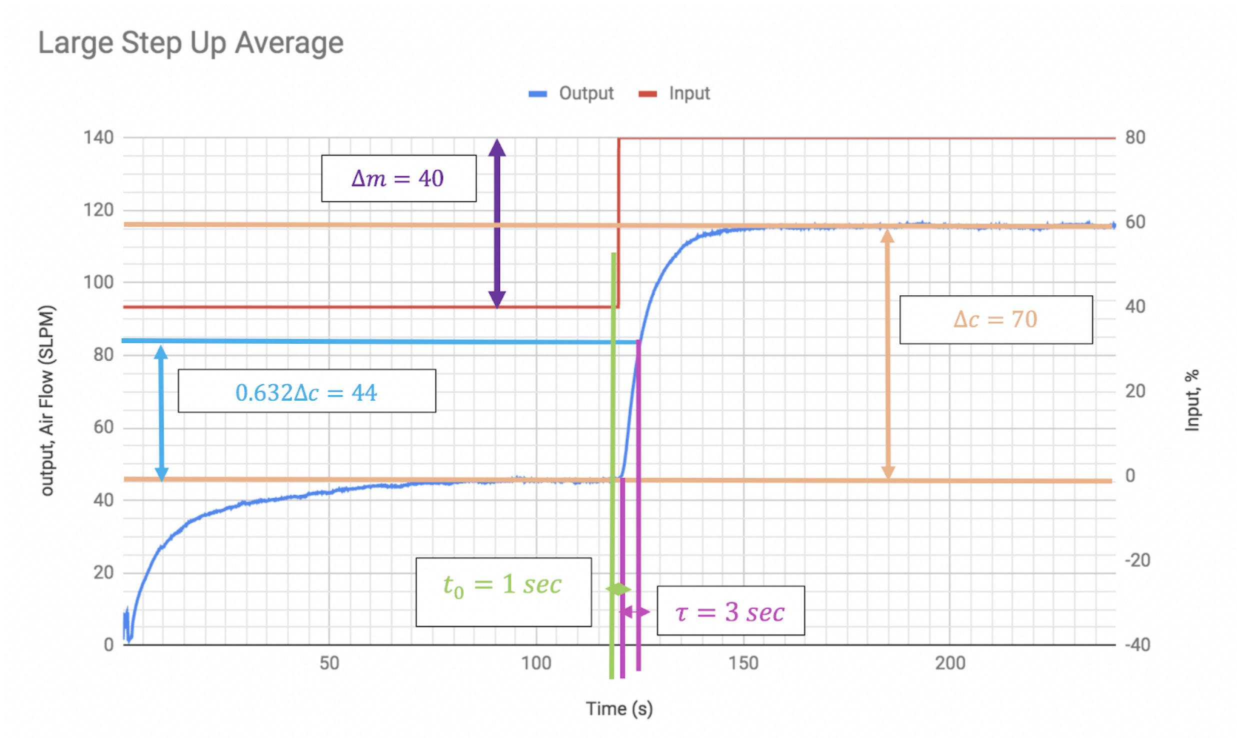

Figure 16. Parameters for an Example Step Up.

The third experiment is Frequency where students have to find the frequency response time of the absorber. The frequency response of a system is when a first-order process is forced by a sinusoidal input and shows how the output characteristics depend on the frequency of the input signal. Students will have to find the amplitude ratio, AR, the phase angle in radians, and the uncertainty for both. Students will have to test various frequencies and determine how the amplitude ratio and phase angles are affected by the change. Figure 13 shows what a response would look like.

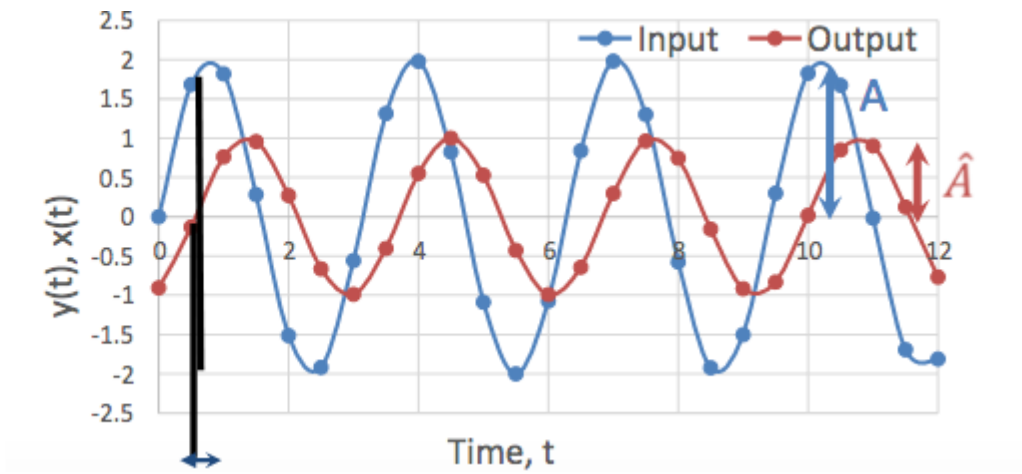

Figure 17. Attenuation and Time Shift between Sine Waves [28]

The final lab students are required to complete for ENCH 3280L is controller tuning. In this lab, students must observe the time response of the output function of the absorber to a proportional (P) an proportional-integral (PI) controller input. Students must adjust the feedback controller parameters to find a specific response of the system. The Ziegler-Nichols' method can be used to find control parameters but first bringing the system as close as possible to the desired operating point. Then, the students have to increase the gain until there are sustained oscillations in the process measurement after a step up has been applied. The student will then be able to calculate control parameters and measure the critical period of the sustained oscillations [29].

Students also need to find the PI controller parameters using the ITAE method. For this method, they similarly choose an initial set point and a step change. However, students have to find integral error criteria for the absolute error, squared error, and time-weighted absolute error. ITAE is generally preferred over Ziegler-Nichols' because it results in the most accurate controller settings. At the end of this lab, students must deliver a table of calculated controller values, plots for the inputs and outputs versus time, and plots of the input and output versus time using the critical controller gain.

Adsorber

LabVIEW Code

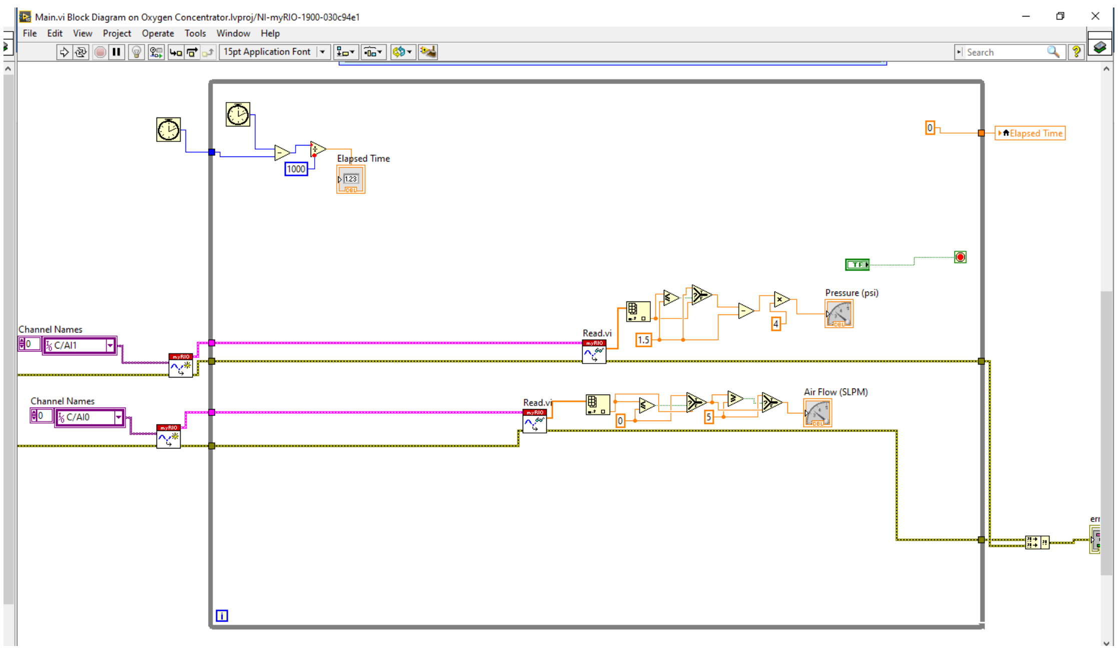

Figure 18. Adsorber Code for Air Flow and Pressure Sensor

This is the code set up for the user to read the pressure and air flow at the exit of the system. The myRIO opens the analog input channels 0 and 1, then reads the voltage sent to it and converts it into psi or SLPM for the user to see.

The following code represents how the solenoid valves are controlled. This is a timed loop that refreshes every 6250ms or 6.250 seconds. Feedback nodes are used to keep the data from the previous loop into the next. You can enable or disable the feedback loop using the enable terminal. If the enable terminal is set to TRUE, the Feedback Node runs as you configure it to run in the properties dialog box or from the shortcut menu of the node. If the enable terminal is set to FALSE, the Feedback Node ignores the input value and returns the value from the last execution or iteration when the enable terminal was TRUE. The Feedback Node continues to return this value until the execution or iteration after the enable terminal changes to TRUE. One solenoid is set to TRUE and the other to FALSE so every time the loop refreshes, they switch values. The solenoids are controlled by the Digital Output function on the myRIO (C/DIO1 and C/DIO5).

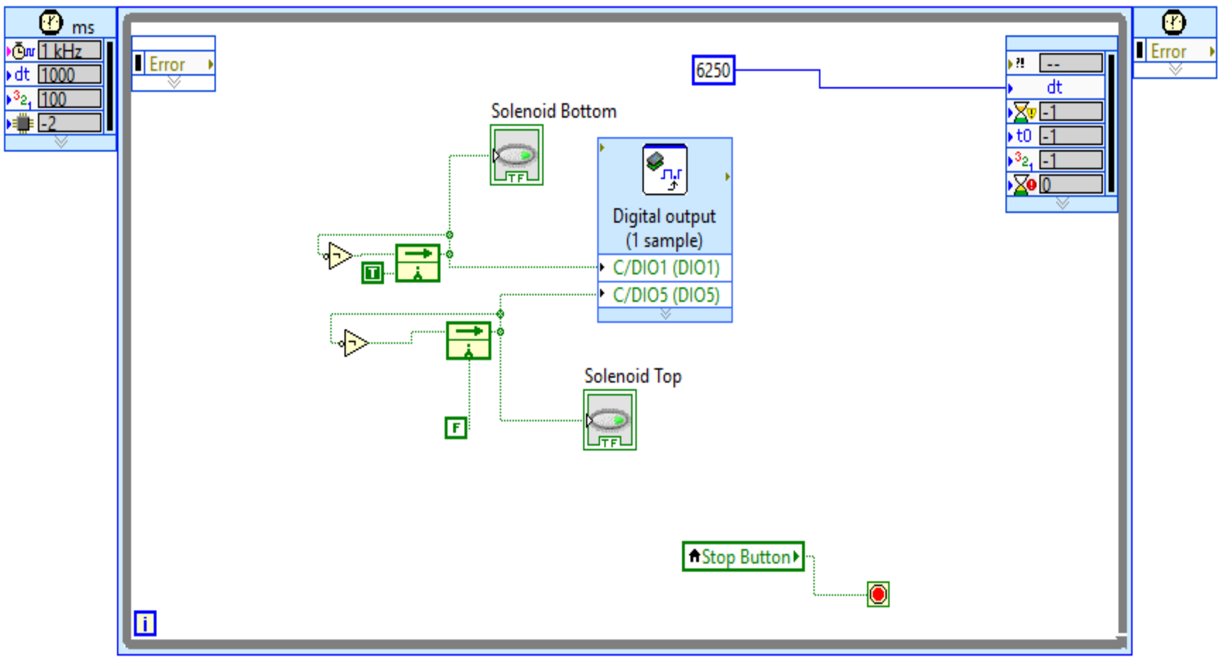

Figure 19. Solenoid Valve LabVIEW Code

Hardware and myRIO Implementation

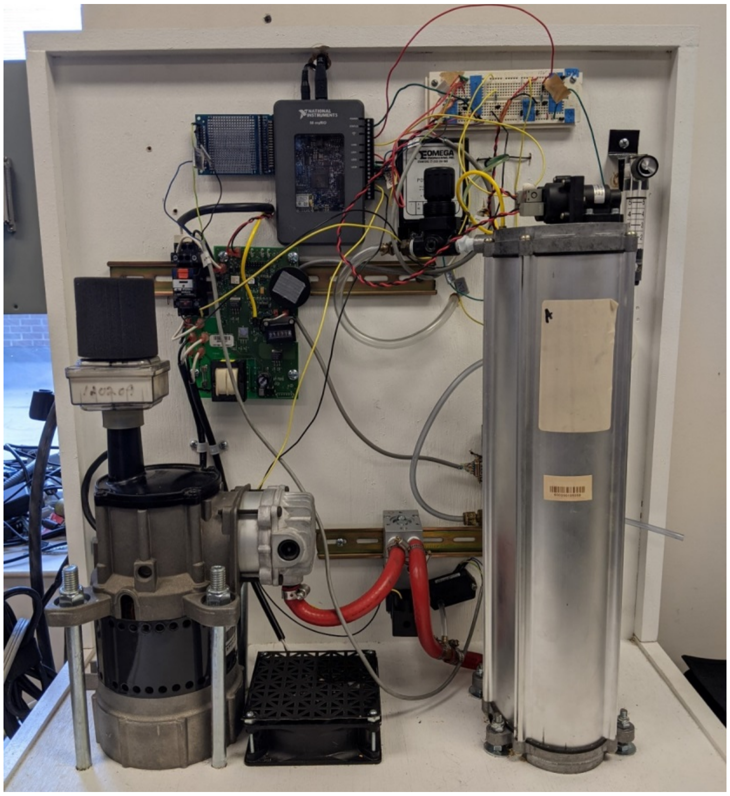

Figure 20. Adsorber System

The Adsorber system consists of 2 main parts: a compressor and a desiccant bed. The compressor pumps pressurized air into the bed. The desiccant bed is filled with a find adsorbent material similar to sand in shape and size. This material adsorbs the nitrogen and CO_2 in the air and releases it through the bottom of the chamber. All that is left in the chamber is oxygen. The desiccant bed has 2 main chambers. They are operating with a solenoid valve which only allows air to enter one chamber at a time at an interval of 6.25 seconds [19]. After 6.25 seconds, the bed is fully saturated with nitrogen so air enters the other chamber while the first bed releases its nitrogen from the bottom. The beds continue to switch every 6.25 seconds and this allow for continual flow of oxygen out of the chamber. The solenoid valves operate at 12V which is too high for the myRIO to control, so a circuit board with a transistor was installed to reduce the voltage required for control.

At the exit of the chamber, a flowmeter is attached. This is controlled with an analog input channel on the myRIO. The expected voltage for the Omega FMA 1718 flowmeter is 0-5 VDC [30]. The myRIO can see the voltage and interpret it to a flowrate in L/min. Students also will have the ability to control the pressure going into the chamber. Safety measures are in place where if pressure is too high, the pressure regulator will vent out some air. This is connected to the C/AO0 channel on the myRIO.

The compressor operates on a switch installed into the preexisting circuit board. This is a physical switch that must be flipped to send the required 115V to the compressor. In order for the compressor to be controlled by the myRIO, a relay PT switch was installed. Like the solenoid valves, this is connected to a transistor on a circuit board to lower the voltage and allow the relay switch to be controlled by the myRIO. An image of the relay switch can be found below.

Figure 21. Relay Switch [31]

Experiment Design for Students

For pressure swing adsorption, there are several types of adsorbent materials that can be used. Currently the Adsorber has zeolites as the adsorbent material. Zeolites are microporous crystalline structures with a lifespan of about 10 years. There are various ways of controlling adsorption with zeolites because they separate molecules based on size, shape and polarity. Metal cations (calcium, sodium, or silver) are bound to the zeolite structure. This creates an electrostatic interaction between the cation and the molecules being adsorbed [32].

LiAgX zeolite is useful for removing nitrogen from oxygen with 96.42% oxygen purity, but the drawback for this zeolite is the selectivity of argon to oxygen is approximately 1:1. AgA zeolite has an argon to oxygen selectivity of 1.63 to 1 and a nitrogen to oxygen selectivity of 5 to 1. For the Adsorber experiment, students can use different types of zeolites and create a material balance such as the following to find out which type of zeolite adsorbs the most nitrogen and argon from ambient air. One design would just be the LiAgX zeolite, another would be AgA zeolite, a third would be both zeolites mixed and a fourth would be separated LiAgX and AgA zeolites.

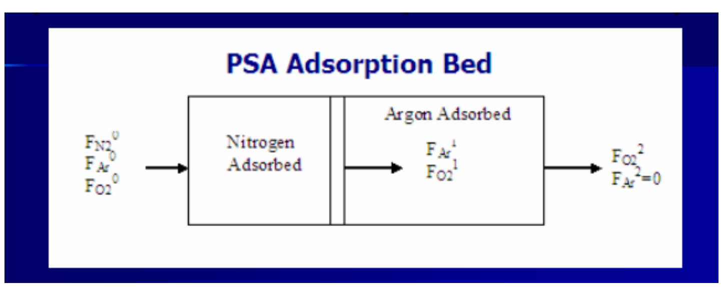

Figure 22. Equilibrium Adsorption Theory [33]

For the Adsorber experiment, students will be able to gain some hands-on experience with LabVIEW. The relay power switch is completely wired to the system, as well as the pressure regulator. Students will have to figure out how to implement code to activate these. This will involve opening the myRIO analog output channels they are controlled by, using the WRITE VI to send voltages to the myRIO and monitor how the pressure, air flow and concentration of oxygen are affected by this. The oxygen sensor will be installed when it arrives.

Students will be able to analyze how oxygen concentration differs between adsorbents using the oxygen sensor and will gain hands-on experience with LabVIEW. The following table is the tabulated results of an example experiment on zeolite design analysis done by students at the University of Oklahoma. Students at UTC will be expected to tabulate their results in this format.

Column, Zeolite, and Flow Specifications for PSA Designs			
LiAgX Only		**AgA Only**	
Recovery of Inlet Oxygen	27	Recovery of Inlet Oxygen	20
Inlet Flow Rate (L/s)	1,007	Inlet Flow Rate (L/s)	1,325
Mass of LiAgX Zeolites (kg)	4,342	Mass of LiAgX Zeolites (kg)	5,714
Volume Column (cm^3)	4,058,324	Volume Column (cm^3)	5,339,900
Area Column (cm^2)	5,027	Area Column (cm^2)	5,027
Length Column (cm)	807	Length Column (cm)	1,062
50/50 Mixture		***LiAgX/AgA***	
Recovery of Inlet Oxygen	25	Recovery of Inlet Oxygen	**35**
Inlet Flow Rate (L/s)	1,060	Inlet Flow Rate (L/s)	**362**
Mass of LiAgX Zeolites (kg)	2,286	Mass of LiAgX Zeolites (kg)	**1,614**
Mass of AgA Zeolites (kg)	2,286	Mass of AgA Zeolites (kg)	**601**
Volume Column (cm^3)	4,271,920	Volume Column (cm^3)	**2,069,402**
Area Column (cm^2)	5,027	Area Column (cm^2)	**5,027**
Length Column (cm)	850	Length Column (cm)	**412**

Figure 23. Zeolite Design Analysis [33]

CHAPTER 4: Conclusion

Conclusion

The Adsorber will provide students with exposure to uncommon unit operations in undergraduate chemical engineering courses. In Unit Operations Laboratory, students will be able to control the pressure of the air exiting the compressor and entering the sieve bed. They will also be able to control the timing of how long the air remains in the chamber before exhausting. Students can use various types of zeolites to determine which gives the highest oxygen concentration out of the vessel.

The Controls System Lab at UTC requires students to conduct the following types of experiments throughout the course: Steady State Operating Curve (SSOC), Step, Frequency, and Tuning. The program written in LabVIEW is set up to where the students can choose the type of experiment they would like to conduct and input values based on the type of experiment they are running. The student can then see a real-time graph of air/water flow vs. time along with gauges that show the student what the air and/or water flow is with correct units. A sub VI is set up to send an email to the student based off of their UTC ID that contains all of their data from that experiment.

The Absorber is currently being used in the ENCH 3280 Laboratory and will continue to be used for this course. While the Adsorber is not yet fully implemented, having these hands-on projects for students to experience dramatically increases their understanding of the subject, and when students take senior level chemical engineering courses, the presented material about adsorption and absorption will not be unfamiliar to them.

Future Work

Oxygen sensors still need to be installed and calibrated in order to be functional on the Adsorber system. Future student(s) will need to coordinate with Jason McDowell in the CECS Technical Support department at UTC to install these sensors when they arrive. A written laboratory procedure for testing various zeolites will be written along with what results students are expected to include in their laboratory report. The Absorber system has a password protected block diagram, but in order for students to write their own code for controlling the Adsorber, no password will be required. However, students will be expected to delete their changes to the program after they have finished working on it in order to prevent the next student who uses it from copying their work. Jason McDowell set up the majority of the wiring and sensors installed on the Adsorber, and future student(s) will need to coordinate with him to obtain written documentation on how he set up all of the wiring.

Works Cited

[1] R. Baheti and H. Gill, "Cyber-Physical Systems: The Impact of Control Technology," 2011.

[2] Kim and Kumar, "Cyber-Physical Systems: A Perspective at the Centennial," *Proceedings of the IEEE,* 2012.

[3] Tennessee Higher Education Commission, "Articulation and Transfer in TN," *Higher Education,* 2016.

[4] Rhine, Milligan and Nelson, "Alleviating Transfer Shock: Creating an Environment for More Successful Transfer Students," *Community College Journal of Research & Practice,* pp. 443-453, 2000.

[5] T. Rhine, D. Milligan and L. Nelson, *Alleviating Transfer Shock: Creating an Environment for More Successful Transfer Students,* Community College Journal of Research & Practice, 2000.

[6] F. Laanan, *Studying Transfer Students:Part II: Dimensions of Transfer Students' Adjustment,* 2007, pp. 37-59.

[7] J. Meyer and R. Land, Threshold Concepts and Troublesome Knowledge: Linkages to Ways

of Thinking and Practising within the Disciplines, Improving Student Learning- Ten Years on, 2003.

[8] Land, Cousin, Meyer and Davies, "Implications of Threshold Concepts for Course Design and Evaluation," *Overcoming Barriers to Student Understanding: Threshold Concepts and Troublesome Knowledge,* pp. 195-208, 2006.

[9] Parker and McGill, "Modular Approach and Innovations in an Engineering Program Design," *Threshold Concepts in Practice,* 2016.

[10] M. E. a. H. J. Porter, How Smart, Connected Products are Transforming Competition, vol. 11, Harvard Business Review, 2014, pp. 64-88.

[11] M. P. V. E. Millar, How Information gives You Competitive Advantage, Harvard Business Review, 1985, pp. 149-160.

[12] C. Elliott, V. Vijayakumar and W. Zink, National Instruments LabVIEW: A Programming Environment for Laboratory Automation and Measurement, vol. 12, San Francisco, CA: JALA: Journal of the Association for Laboratory Automation, 2007, pp. 17-24.

[13] P. Orduna, J. Garcia-Zubia and L. Rodriguez-Gil, Using LabVIEW Remote Panel in Remote Laboratories: Advantages and Disadvantages of LabVIEW, IEEE, 2012.

[14] Labview Advanced Virtual Architects, LAVA.org.

[15] L. Kucka, I. Muller, E. Kenig and A. Gorak, On the modelling and simulation of sour gas absorption by aqueous amine solutions, vol. 58, Dusseldorf: Chemical Engineering Science, 2003, pp. 3571-3578.

[16] P. Piergiovanni, Introductory Adsorption Laboratory Experiment, American Society for Engineering Education, 2012.

[17] Delta Adsorbents, Benefits of Silica Gel Desicant Packets, Delta Adsorbents, 2019.

[18] Respironics, *Millennium Oxygen Concentrators: Service & Technical Information,* Murrysville, PA: Millennium Service & Technical Information, 2007.

[19] SMC, *3 port Solenoied Valve Rubber Seal.*

[20] Watchdog.

[21] National Instruments, NI myRIO User Guide and Specifications.

[22] 8-channel backplane.

[23] Analog Devices, 5B Sries 16 channel backplane.

[24] Company, Hass Manufacturing, *EPV Owner's Manual,* Averill Park, New York: Hass Manufacturing Company, 1998.

[25] Analog Devices, *Isolated Current Output 5B39,* Norwood, MA: Analog Devices, 2004.

[26] Micro Motion, *Model RFT9739 Field-Mount Transmitter,* Wilmington, Delaware: Fisher-Rosemount, 2000.

[27] Omega Engineering, *High Flow-Rate Gas Mass Controllers and Meters for Clean Gases,* Omega.

[28] S. Palchoudhury, *Section: Step Response Powerpoint Presentation,* 2020.

[29] F. Haugen, Ziegler-Nichols' Closed-Loop Method, TechTeach, 2010.

[30] Omega Engineering, *FMA 1700 & 1800 Mass Flowmeter,* Omega.

[31] TE Connectivity Relay Products, *General Purpose Relays,* Tyco Electronics Corporation, 2015.

[32] R. T. Yang, *Comparison of Activated Carbon and Zeolite 13X for CO2 Recovery from Flue Gas by Pressure Swing Adsorption,* Buffalo: Departnment of Chemical Engineering, State University of New York at Buffalo, 1995.

[33] B. Ashcraft and J. Swenton, *99% Oxygen Production with Zeolites and Pressure Swing Adsorption,* Chemical, Biological and Materials Engineering.

APPENDIX

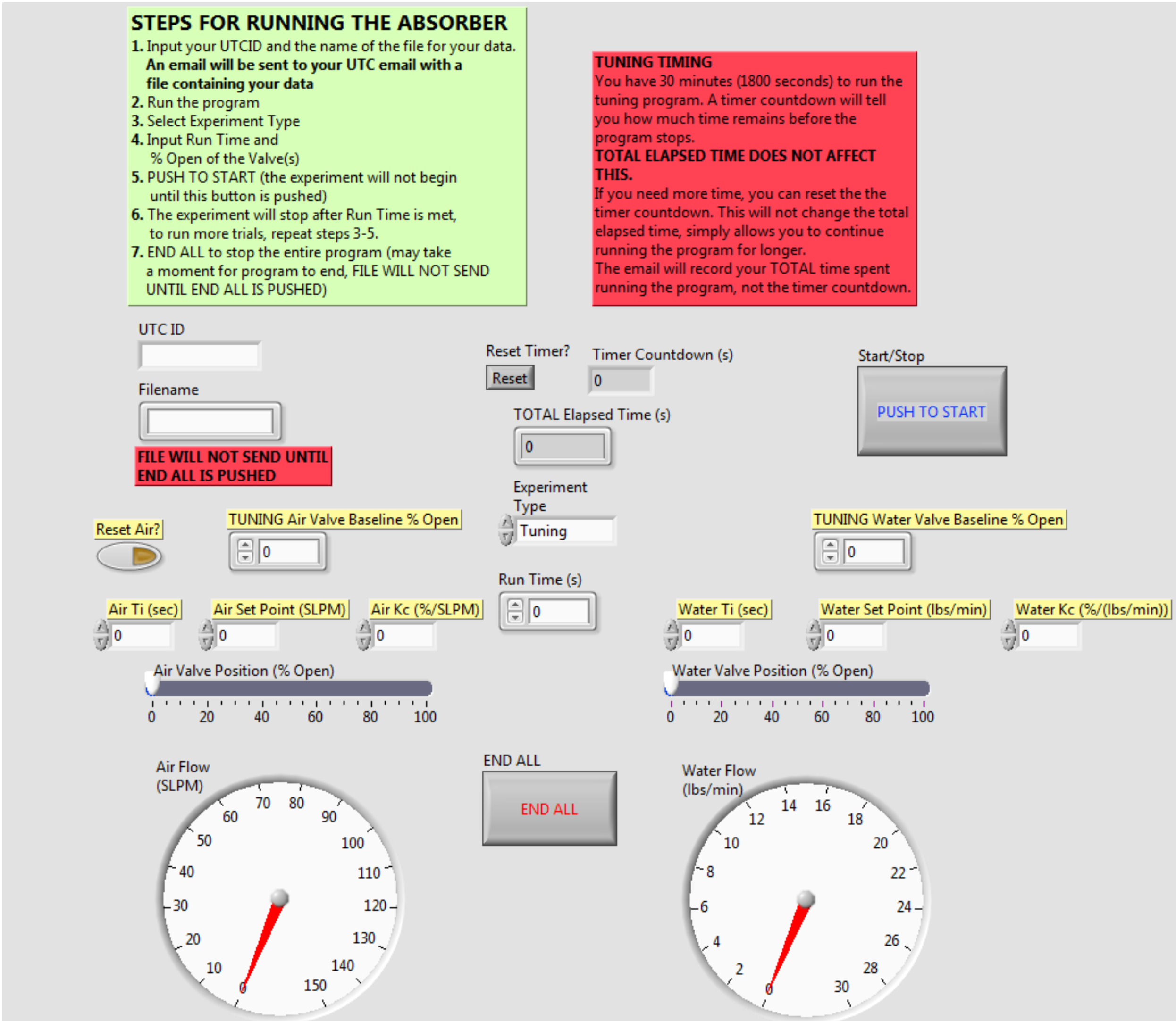

Figure 22. Tuning Front Panel

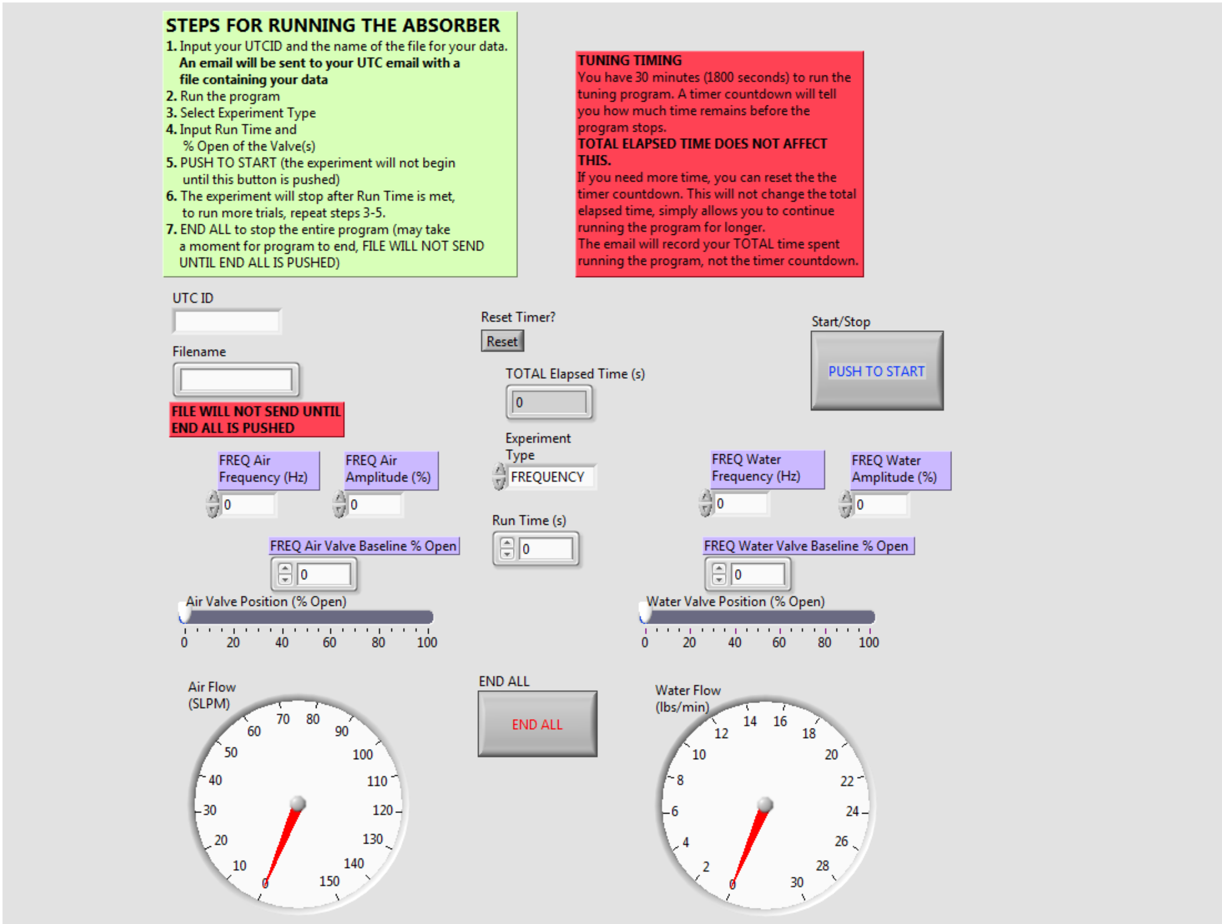

Figure 23. Frequency Front Panel

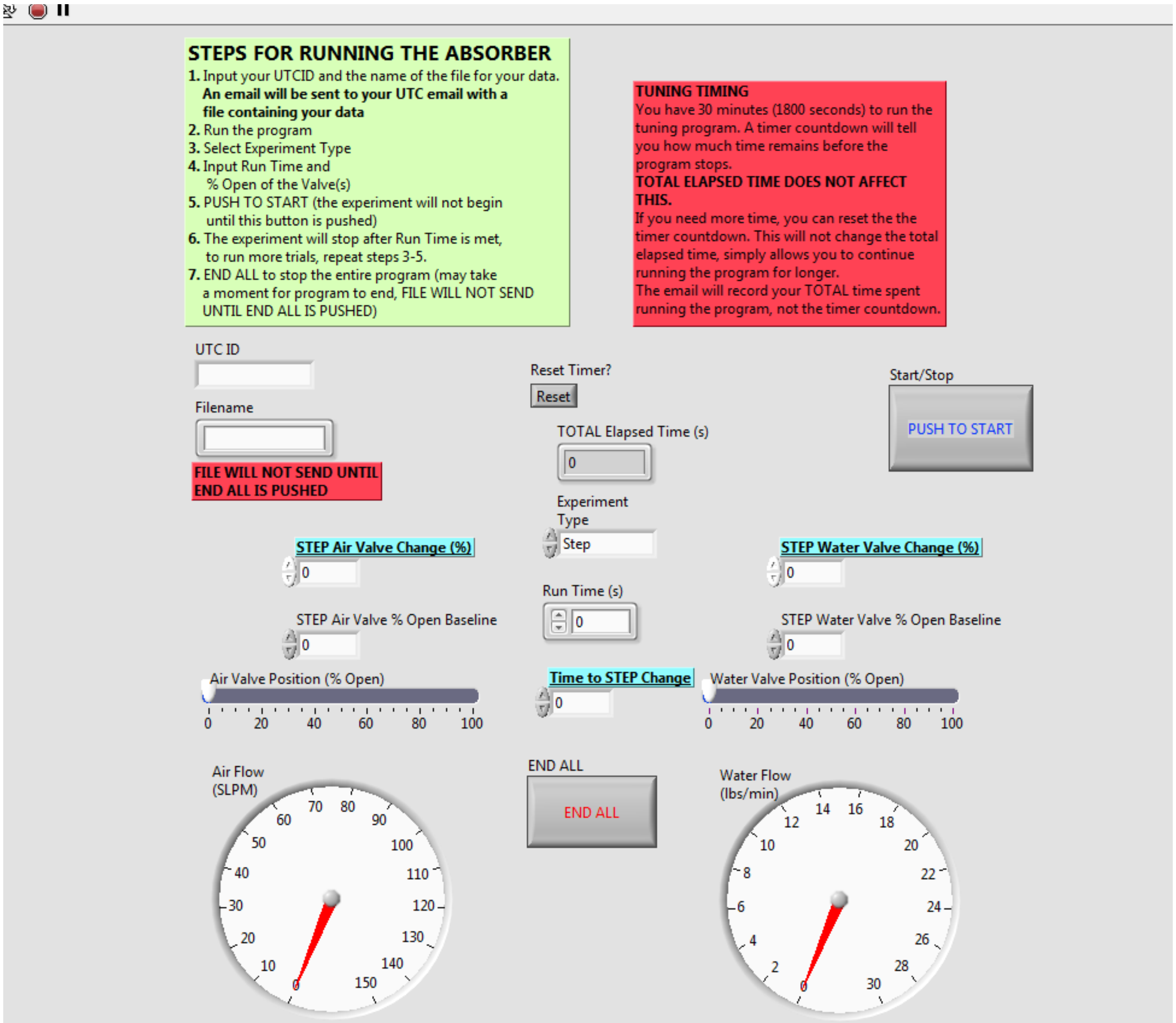

Figure 24. Step Front Panel